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J/ψ production measurements by the PHENIX experiment

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Abstract. Quarkonia suppression is considered to be one of the key probes of the Quark Gluon Plasma (QGP) created in heavy ion collisions. The PHENIX experiment has measured J/ψ production in a variety of colliding systems. Measurements made in p+p collisions show good agreement with pQCD predictions and serve as baseline for other systems at the same collision energy. The cold nuclear matter contribution to the suppression is constrained through measurements in d+Au collisions. In Au+Au, the suppression observed at mid rapidity is smaller than that at forward rapidity, a tendency opposite to what is expected from the higher gluon density at mid rapidity. The results will be presented and discussed in this article.

PACS. 25.75.-q Relativistic heavy-ion collisions – 12.38.Mh Quark-gluon plasma – 25.75.Ld Collective flow – 13.20.Gd Decays of J/ψ, Υ, and other quarkonia

1 Introduction

Ever since color screening was proposed [1] as a mechanism leading to *anomalous* suppression of J/ψs in deconfined medium beyond *normal* hadronic absorption, a substantial amount of theoretical and experimental effort has been devoted to the exploration of this phenomenon. The CERN SPS experiments NA38, NA50 and NA60 were the first to investigate the prediction by measuring J/ψ suppression in a variety of colliding systems and energies. The results show a statistically significant anomalous suppression in central Pb+Pb [2] and In+In [3] collisions, that can be interpreted in terms of melting in the QGP.

The PHENIX experiment at RHIC has also measured the production of J/ψ in a variety of colliding systems, and provided further insights by exploring this phenomenon at higher energies. J/ψs are detected in PHENIX through their dielectron decay at mid rapidity ($|y| < 0.35$) and through their dimuon decay at forward rapidity ($1.2 < |y| < 2.4$). J/ψ suppression is characterized by a ratio called the *nuclear modification factor*, obtained by normalizing the J/ψ yields in heavy ion collisions (dN_{AB}) by the J/ψ yields in p+p collisions at the same energy (dN_{pp}) times the average number of binary inelastic nucleon-nucleon collisions ($< N_{coll} >$):

$$R_{AB}(y, p_T) = \frac{dN_{AB}(y, p_T)/dydp_T}{< N_{coll} > dN_{pp}(y, p_T)/dydp_T}. \quad (1)$$

If the heavy ion collision is a superposition of independent N_{coll} inelastic nucleon-nucleon collisions, R_{AB} will be equal to unity, whereas it will be larger than one in case of enhancement and lower than one in case of suppression.

At typical RHIC energies ($\sqrt{s_{NN}}$ = 19.6 - 200 GeV), J/ψs are dominantly produced through gluon fusion. The J/ψ yield is therefore sensitive to gluon shadowing [1]. Part of the ground state charmonia yield also comes from feed down of excited states (ψ' and χ_c), and can contribute up to $\sim$ 40% to the total J/ψ yield. Preliminary measurements from PHENIX gives 8.6±2.5% of J/ψ coming from ψ', and upper limit of 42% on the χ_c contribution at the 90% confidence level. In subsequent stages of the collision involving heavy ions, there are a number of competing mechanisms that can enhance or suppress the J/ψ yield. The two major contributors to the suppression are absorption by nuclear fragments from incident nuclei, and an eventual melting in the QGP. Finally it is not impossible that a pair of uncorrelated c and $\bar{c}$ quarks that are close enough in phase space recombine to form a bound charmonium state and enhance the J/ψ yield.

2 Baseline and cold nuclear matter effect measurements

The differential cross section of J/ψ in p+p collisions as a function of rapidity measured by PHENIX is shown in Fig. 1 [4]. In addition to providing normalization cross sections essential for the calculation of R_{AA} as in Eq. 1, J/ψ measurements in p+p collisions constrain the poorly understood J/ψ production mechanism. In the same figure, predictions from various LO and NLO calculations are shown. The current precision does not discriminate

[1] Shadowing refers to the depletion of low momentum partons in nucleons bound in nuclei as compared to free nucleons.

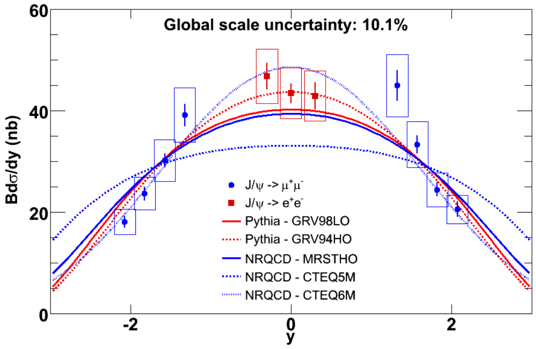

Fig. 1. J/ψ cross section vs. rapidity in p+p collisions.

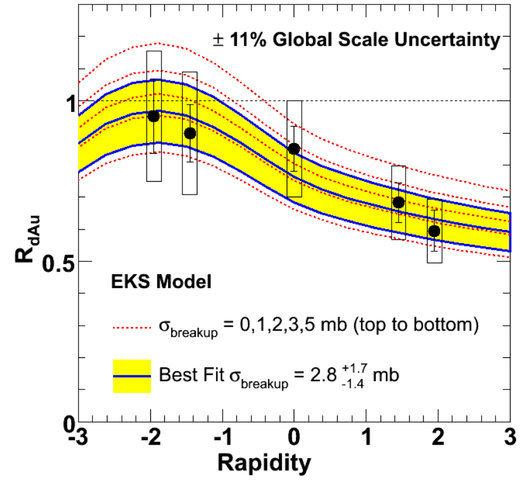

Fig. 2. J/ψ R_{dA} in d+Au collisions vs. rapidity.

between the models, but there is potential for improvement when higher luminosity becomes available.

Additional constraint on the production models can imposed through polarisation measurements. The color octet and color singlet models of J/ψ production predict strong transverse polarisation at high p_T and no polarization at all respectively. A preliminary measurement by PHENIX at forward rapidity, reported here for the first time, gives $\lambda = 0.005^{+0.160}_{-0.184}$ [2] for $p_T < 6$ GeV/c, implying neither transverse nor longitudinal polarisation. If this trend is confirmed at high p_T, it would support the color singlet models. Unfortunately most calculations in the framework of the color singlet model largely under predict the total cross section with the exception a recent calculation [5] that claims to reproduce the total cross section and absence of polarization together with the form of the p_T spectra. Despite these advances, a clear picture of the production mechanism of J/ψ is not available yet.

Nuclear absorption and shadowing, collectively referred to as *cold nuclear matter effects (CNM)* can be constrained by measurements in proton (or light ion) on heavy ion collisions. In PHENIX this was performed in deuteron-gold collisions. The resulting suppression ratio R_{dAu} is shown in Fig. 2 [6] as a function of rapidity, where the positive rapidity coincides with the deuteron going direction. J/ψs detected in different rapidity regions probe specific gluon x_2 regions [3]. Forward rapidity corresponds to $x_2 \sim 0.002$ - 0.01 where the depletion due to shadowing is important whereas backward rapidity corresponds to $x_2 \sim 0.05$ - 0.2 where a slight enhancement due to anti-shadowing is expected. The rapidity dependence of R_{dA} therefore reflects the gluon shadowing, whereas the global vertical scale is determined by the amount of *normal* absorption.

To quantitatively disentangle the shadowing component from the absorption component, a rapidity dependence using two shadowing schemes, EKS [7] and NDSG [8] was fitted to R_{dA} leaving the overall vertical scale a free parameter to account for the absorption [6]. J/ψ absorption cross sections of $2.8^{+1.7}_{-1.4}$ mb and $2.2^{+1.6}_{-1.5}$ mb were obtained for EKS and NDSG schemes respectively. This is in agreement with the absorption cross section reported by the SPS of 4.2 ± 0.5 mb [9] but such a comparison should not be taken at face value because shadowing is not taken into account in the SPS [4] absorption cross sections evaluation. A much more stringent constraint is expected form a 30× higher luminosity data that was collected by PHENIX in 2008.

3 Anomalous suppression in heavy ion systems

PHENIX has also measured J/ψ suppression in Au+Au [10] and Cu+Cu [11] collisions at $\sqrt{s_{NN}} = 200$ GeV. The J/ψ R_{AA} in Au+Au collisions as a function of the number of participants N_{part}, at forward and mid rapidity ranges is shown in Fig. 3 [10] together with data points from NA38, NA50 and NA60 experiments. The R_{AA} goes down to ~ 0.2 for the most central Au+Au collisions (large N_{part}), and approaches unity for peripheral ones (small N_{part}). To see the extent of anomalous suppression, extrapolations of the CNM and shadowing constraints obtained from d+Au measurements were calculated using a model dependent method which assumes the above mentioned shadowing schemes as well as with a data driven method which has minimal model dependence. The result [6] from both methods is a statistically significant suppression beyond CNM extrapolation in the most central forward rapidity Au+Au collisions, less pronounced at mid rapidity Au+Au or in Cu+Cu collisions.

[2] λ is the calculated from a fit $\frac{d\sigma}{dcos\theta} = A(1 + \lambda cos^2\theta)$ to the differential production cross section as a function of the polar angle θ between the momentum of the decay leptons in the rest frame of the J/ψ and momentum J/ψ in the lab frame. $\lambda > 0$ (< 0) implies transverse (longitudinal) polarization.

[3] By x_2, we refer to the parton longitudinal momentum fraction in the nucleus.

[4] Taking into account nuclear PDF modification would increase the SPS absorption cross section, because the SPS rapidity corresponds to the anti-shadowing regime, requiring more absorption to account for the observed suppression.

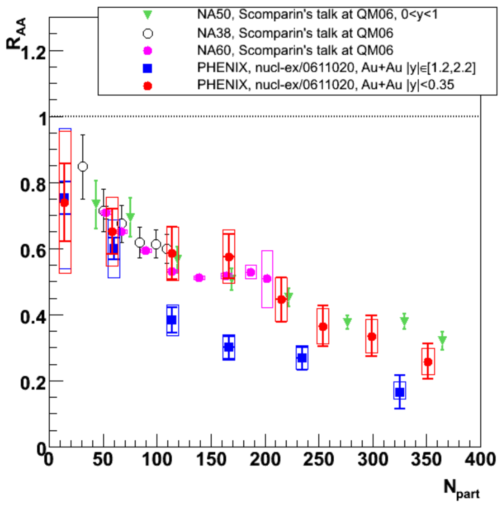

Fig. 3. J/ψ R_{AA} vs. N_{part} at SPS compared to RHIC.

The data show two features that contradict local density induced suppression models. The mid rapidity suppression is lower than the forward rapidity suppression (cf. Fig. 3), despite experimental evidence [5] that energy density is higher at mid rapidity than at forward rapidity. The same remark holds for the comparison between R_{AA} at mid rapidity in PHENIX and R_{AA} at SPS [6] (cf. Fig. 3). The two are in agreement within error bars, a surprising result considering that the energy density reached at RHIC is larger than the one reached at SPS. A number of explanations have been put forth, including sequential melting, where only ψ' and χ_c are dissociated leading to a suppression of only the feed down component of the J/ψ yield [13], coupled to gluon saturation that leads to a lower charm quark yield at forward rapidity [14].

4 Regeneration

A strong regeneration of J/ψ from uncorrelated c and $\bar{c}$ quarks is another good candidate to explain the tendency of R_{AA} as a function of rapidity at RHIC. This is supported by the high charm quark yield measurements [15] ($\sim$10 $c\bar{c}$ pairs are created in the most central Au+Au collisions). A number of model predictions that incorporate regeneration have been proposed [16] and all of them reproduce qualitatively the rapidity dependence of J/ψ R_{AA} observed by PHENIX.

However, important inputs to regeneration models such as the precise number of $c\bar{c}$ pairs available for recombination and the phase space conditions for recombination to take place are poorly constrained. It is thus very compelling to have a direct experimental check of regeneration. The J/ψ elliptic flow is one candidate. Elliptic flow refers to the azimuthal angle correlation of particle emission with respect to the reaction plane orientation [7]. It is quantified by the second Fourier coefficient v_2 of the azimuthal angle distribution of identified particles. The measured v_2 of electrons from D and B meson decays is remarkably high [17]. This is believed to originate from the elliptic flow of underlying charm and beauty quarks. J/ψs from recombination should inherit the charm quark flow, resulting in a higher v_2 than the case of direct production in hard collisions.

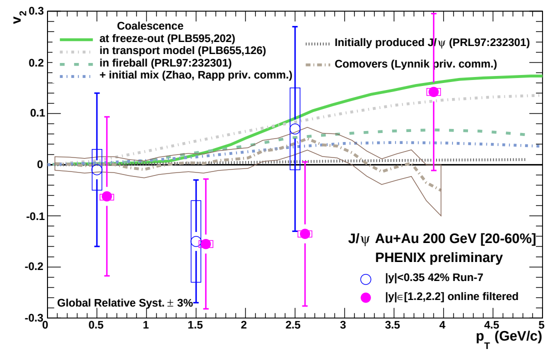

Fig. 4. J/ψ v_2 vs. p_T measurement by PHENIX.

The first measurement of J/ψ v_2 at RHIC energy performed by PHENIX at forward [18] and mid rapidity is shown in Fig. 4 as a function of transverse momentum. Predictions from models that assume various amounts of recombination from none to full coalescence at freeze out are plotted together. Data points are compatible within the error bars simultaneously with zero flow as well as with the model that predicts maximum flow. The results at the two rapidity windows show a similar trend, albeit with large uncertainties. Assuming Gaussian errors and taking the p_T integrated values of v_2 measured at any one of two rapidity regions (10.0$\pm$10.0% at $|y|$ <0.35 and -9.3$\pm$9.2% at 1.2< $|y|$ <2.2), the probability that the actual v_2 is positive is of the order of 15%. It is to be noted that a much larger sample will probably be needed to be able to discriminate between the different models more quantitatively. Such data is expected to be available at future RHIC runs.

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[5] The rapidity density of charged particles which increases with the deposited energy peaks at mid rapidity [12].

[6] Care must be taken when comparing with SPS, because the CNM effects are not the same at the two energies.

[7] The reaction plane is the plane defined by the beam axis and the line joining the center of colliding nuclei. It is measured in PHENIX from azimuthal angle distribution of charged particles close to beam rapidity.

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